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GQ Lup and its common proper motion companion

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Abstract. Recently, Neuhäuser et al. (2005a) presented evidence for a sub-stellar, common proper motion companion to GQ Lup. With two theoretical mass estimates, both below the Deuterium burning minimum mass limit, the companion is probably a planet imaged directly. We present here a more detailed astrometric analysis of the GQ Lup system, using all the (different) proper motions published for the primary. The common proper motion is significant in all cases, also when taking into account the error in parallax or distance (140 ± 50 pc). When using the weighted mean, the significance for common proper motion of GQ Lup and its companion is $7\,\sigma$ + $4\,\sigma$ for no change in separation plus $8\,\sigma$ for no change in position angle. We also discuss the question, whether GQ Lup and its common-proper motion companion are not bound, but share the same or similar proper motion as two independent members of the Lupus T association, which is a moving group, where most members should have the same motion anyway. Given our discussion, this hypothesis can be rejected by several σ: The probability to find by chance an L-dwarf fainter than $\mathrm{K_S} = 14$ mag within 0.7325″ with (almost) the same proper motion of GQ Lup is only $\leq 3 \cdot 10^{-10}$. The orbital motion of the system is not yet detected (1.4 ± 2.2 mas/yr), but is probably smaller than the escape velocity (5.3 ± 2.1 mas/yr), so that the system may well be gravitationally bound and stable. This is different for the 2MASSWJ 1207334-393254 system, as we also show.

Key words: GQ Lup A, GQ Lup b, 2M1207, extra-solar planets, late-type stars, astrometry

1. Introduction: GQ Lup and its companion

With $\mathrm{K_S}$ - band imaging using our own imaging data obtained with the Very Large Telescope (VLT) and its infrared adaptive optics camera NAos-COnica (NACO), we detected a ~ 6 mag fainter object $0.7325 \pm 0.0034''$ west of the classical T Tauri star GQ Lup, located in the Lupus I cloud. Using archival data from the Subaru telescope adaptive optics camera (CIAO), see Fig. 1, and the Hubble Space Telescope (HST) Planetary Camera (PC), see Fig. 2, we could show that it is clearly a co-moving companion (Neuhäuser et al. 2005a, henceforth N05a), but orbital motion was not yet detectable.

The NACO K_S - band spectrum yielded $\sim$L1-2 (M9-L4) as spectral type. At 140 ± 50 pc distance (Lupus I cloud), it can be placed into the H-R diagram. According to our own calculations following Wuchterl & Tscharnuter (2003), it has 1 to 3 $\mathrm{M_{Jup}}$. This model takes into account the formation and collapse. A comparison of our spectrum with the GAIA-dusty model (Brott & Hauschildt, in preparation), an update of the AMES-dusty model (Allard et al. 2001), yielded the radius to be $1.2 \pm 0.5\,\mathrm{R_{Jup}}$ and the gravity to be $\log \mathrm{g} = 2.0$ to 3.3 (g in cgs units). For M9-L4 spectral type, the temperature is 2050 ± 450 K. At the given flux of the GQ Lup companion ($\mathrm{K_S} = 13.10 \pm 0.15$ mag at 140 ± 50 pc), this yields a mass of $\leq 2\,\mathrm{M_{Jup}}$ (for $\log \mathrm{g} \simeq 4$ and $2\,\mathrm{R_{Jup}}$, it is $\sim 6\,\mathrm{M_{Jup}}$), see also Neuhäuser et al. (2005b), henceforth N05b.

Mohanty et al. (2004a) measured gravities for isolated young brown dwarfs and free-floating planetary mass objects. Their coolest objects have spectral type M7.5 and gravities as low as $\log \mathrm{g} = 3.125$ (GG Tau Bb). This lead Mohanty et al. (2004b) to mass estimations as low as $\sim 10\,\mathrm{M_{Jup}}$. GQ Lup A is younger than the Mohanty et al. Upper Sco objects. Its companion is at least as late in spectral type, probably even cooler. An object younger and cooler must be lower in mass. The GQ Lup companion is fainter than the faintest Mohanty et al. object (USco 128, $\sim 9\,\mathrm{M_{Jup}}$), so that the mass estimate for the GQ Lup companion would be $\leq 8\,\mathrm{M_{Jup}}$ (see also N05b). However, Reiners[1] argues that some TiO oscillator strength were wrong in some inputs used in Mohanty et al. (2004a,b), so that all temperatures have to be increased by 150 to 200 K, and, hence, also mass estimates. Therefore, the

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[1] see http://www.iac.es/workshop/ulmsf05/pres/reiners.pdf

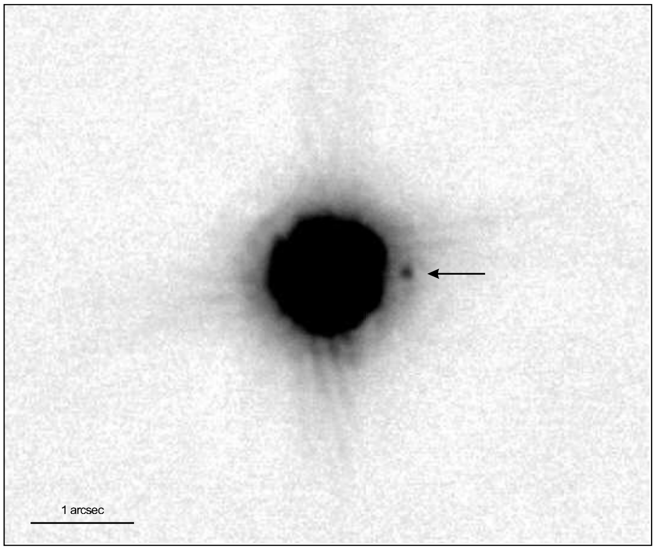

Fig. 1. Subaru image of GQ Lup A and companion b in the L-band.

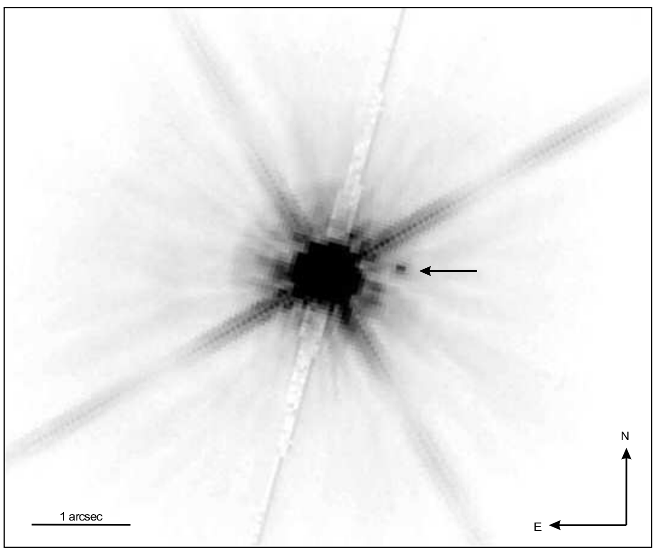

Fig. 2. HST/PC image of GQ Lup A and companion b in filter F606W.

mass estimate for USco 128 and, hence, the upper mass limit for GQ Lup b is now $\sim 15\,\mathrm{M_{Jup}}$.

According to Burrows et al. (1997) and Baraffe et al. (2002), the mass of the companion could be anywhere between 3 and 42 $\mathrm{M_{Jup}}$, as given in N05a. However, these models are not valid at the young age of GQ Lup, so that they are not applicable. According to both Mohanty et al. (2004b) and Close et al. (2005), the Baraffe et al. (2002) models overestimate the masses of young sub-stellar objects below $\sim 30\,\mathrm{M_{Jup}}$, but may underestimate them above $\sim 40\,\mathrm{M_{Jup}}$. This is consistent with our results.

Hence, according to all valid estimations, the mass of the GQ Lup companion is almost certainly below $\sim 13\,\mathrm{M_{Jup}}$, hence probably a planet imaged directly, to be called GQ Lup b. For more details, see N05a and N05b.

We present all the different proper motions published for GQ Lup in section 2 and discuss in section 3 the question, whether the primary star and its faint companion candidate form a common proper motion pair according to all the published proper motions or their weighted mean, also taking into account the error in parallax of GQ Lup. Then, in section 4, we discuss an alternative interpretation, namely that GQ Lup and the faint object, even though sharing the same proper motion and being located within 1″, are not bound, but at slightly different distances, both within the Lupus I cloud. We also compare the orbital properties of the common proper motion companions of GQ Lup and the brown dwarf 2MASSWJ 1207334-393254 (afterwards 2M1207). We conclude in section 5.

Table 1. Proper motions of GQ Lup and the estimated weighted mean

Reference	$\mu_\alpha \cos(\delta)$ [mas/yr]	μ_δ [mas/yr]
Carlsberg Meridian Cat. 1999	-20.2±3.9	-21.8±4.1
Kharchenko 2001	-20.55±3.89	-22.1±4.0
USNO-B1.0 (Monet et al. 2003)	-11.4±14.6	-50±10
UCAC2 (Zacharias et al. 2004)	-18.2±4.6	-22.2±4.7
Camargo et al. 2003	-14±3	-21±3
Teixeira et al. 2000	-27±4	-14±4
weighted mean	-19.15±1.67	-21.06±1.69

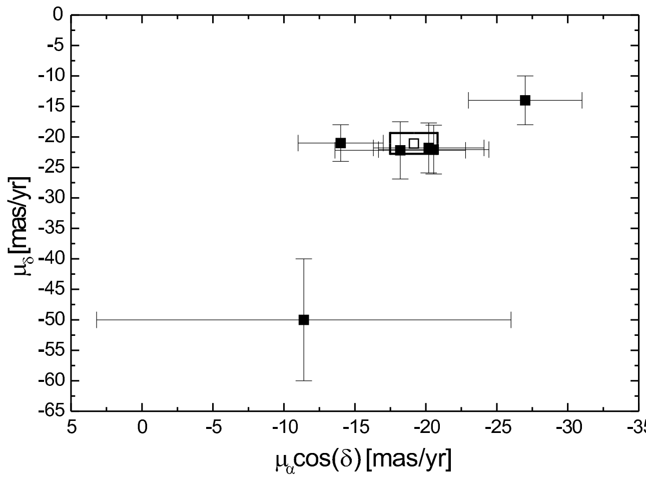

Fig. 3. Proper motions of GQ Lup (see Table 1). The weighted mean is shown in the center (open square) with a 1 σ error box.

2. The proper motion of GQ Lup

To investigate, whether a star and its companion candidate form a common proper motion pair, one has to check, whether the separation and position angle (PA) between the two is constant over time (however, one has to allow for a small change in separation and/or PA because of orbital motion). The epoch difference needed for significant results is given by the proper (and parallactic) motion of the star and the precision achieved in the imaging. The background hypothesis is that the companion candidate has negligible proper and parallactic motion – negligible compared to the primary star.

Table 2. Astrometry of the GQ Lup system (Neuhäuser et al. 2005a)

Telescope	Instr.	Epoch	Separation	PA
		mm/yyyy	[mas]	[°]
HST	PC	04/1999	739±11	275.62±0.86
Subaru	CIAO	07/2002	736.5±5.7	(*)
VLT	NACO	06/2004	732.5±3.4	275.45±0.3
VLT	NACO	08/2004	731.4±4.2	(*)
VLT	NACO	09/2004	735.8±3.7	(*)

(*) No astrometric calibration available for detector orientation, see N05a.

There are six different measurements of the proper motion for GQ Lup given in the literature, see Table 1 and Fig.3. Five of them have a typical precision of 3 to 5 mas/yr. Only the USNO data are an exception with 10 to 15 mas/yr precision. In N05a, we list the two extremes of the remaining five proper motions, namely Teixeira et al. (2000) and Camargo et al. (2003), which are also the best in precision (3 to 4 mas/yr). In Table 1, we also list the computed weighted mean of the six measurements.

3. The common proper motion pair

Here, we present the estimated change in both separation and position angle (PA) for all different proper motions published as well as for the weighted mean – always for two alternatives: Either the two objects form a common-proper motion pair (i.e. separation and PA are constant ± orbital motion), or the faint object is a non-moving background object with negligible proper and parallactic motion, so that only the star moves resulting in a change in separation and PA.

We compare the estimated changes with the actually observed data for GQ Lup in Table 4 (observed astrometric data repeated here in Table 2 from N05a for convenience). We then always estimate the significance, by which we can reject the background hypothesis, see Table 3 and Table4.

Let us first consider the possible effect of parallax uncertainty on the significance of common proper motion. Prior to the Hipparcos mission, the distance of ∼ 140 pc was usually used for the Lupus star forming clouds including the Lupus I cloud with GQ Lup (see e.g. Krautter 1991 and Hughes et al. 1993 for a discussion). The Hipparcos measurements of the T Tauri stars in Lupus confirms this result with 145 ± 50 pc mean distance (see Wichmann et al. 1998 for T Tauri stars known before the ROSAT mission and Neuhäuser & Brandner 1998 for T Tauri stars newly found by the ROSAT mission). However, some members of Lupus also appeared to be as far as ∼ 190 pc (Wichmann et al. 1998), while Knude & Hog (1998) estimated ∼ 100 pc for the distance of Lupus I. More recently, de Zeeuw et al. (1999) list 142 ± 2 pc for Upper Centaurus and Lupus; Nakajima et al. (2000) give ~ 150 pc for Lupus; Franco (2002) argue for ~ 150 pc *as the most probable distance to the dark cloud known as Lupus I*; and Sartori et al. (2003) specify 147 pc. Hence, we use 140 ± 50 pc for the distance towards GQ Lup in both N05a and here. This results in a parallax of 5.3 to 11.1 mas (7.1 mas for 140 pc).

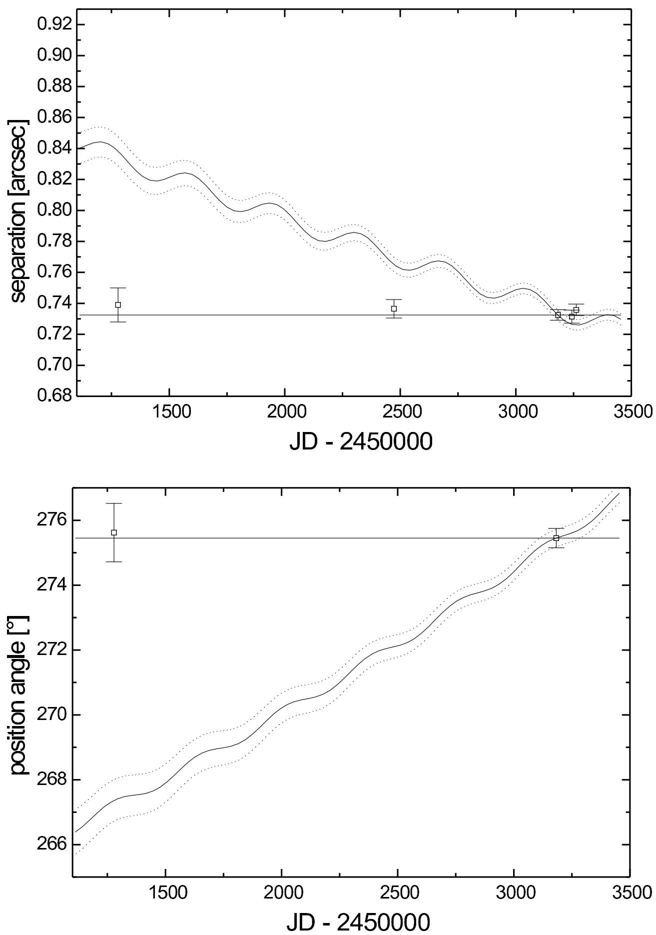

Fig. 4. Change in separation (top) and position angle (bottom) according to weighted mean proper motion (curved full lines) for background hypothesis with uncertainties from errors in proper motion (curved dotted line), which can be rejected; no change in separation (left) or PA (right) as full straight lines with data points from Table 4.

In Fig. 4, we show the expected change in separation and PA compared to the observations, estimated for the mean proper motion of GQ Lup as given in Table 1. Table 3 lists the significance, by which the background hypothesis can be rejected for the three different parallaxes, for both change in separation and PA for two independent different epoch differences available (1999-to-2004 comparing HST to VLT and 2002-to-2004 comparing Subaru to VLT; for the 2004 epoch, we use our deepest NACO image from 25 June 2004).

As can be seen in Table 3, Fig. 5, the effect of parallax uncertainty is very small, only ± 0.3 dex in the significance in separation, and vanishing in significance in PA (only ± 0.1 dex), hence negligible (and actually neglected in N05a). In the remainder of this paper (Table 4), we have used 7.1 mas as parallax (140 pc).

As can be seen from Table 4, there is always high significance for common proper motion. Even in the worst case of the USNO proper motion, which is far off the others and the weighted mean and which has the largest errors, the significance for common proper motion is still above $4\,\sigma$ by rejecting the background hypothesis in PA by $4.2\,\sigma$. For the

Table 3. Comparison of significance for common proper motion for the whole range of parallaxes possible (by using the weighted mean for the proper motion of GQ Lup A): We list all measured separations and position angles (PA) and the estimated separations for the background hypothesis (assuming that the companion does not move). The significance of rejecting the background hypothesis is also given. The 2004 epoch is 25 June 2004, our deepest NACO image. No PA is available for Subaru 2002, because those data were taken by us from the public archive without calibration available.

Parallax	Epoch	Separation [mas]			PA [°]		
		predicted (*)	observed	σ	predicted (*)	observed	σ
5.3 mas	1999-2004	836.2±9.4	739±11	6.7	267.3±0.6	275.62±0.86	7.9
	2002-2004	765.6±4.7	736.5±5.7	3.9			
7.1 mas	1999-2004	838.3±9.4	739±11	6.9	267.4±0.6	275.62±0.86	7.8
	2002-2004	765.1±4.7	736.5±5.7	3.9			
11.1 mas	1999-2004	843.0±9.4	739±11	7.2	267.4±0.6	275.62±0.86	7.8
	2002-2004	764.1±4.7	736.5±5.7	3.7			

Remark: (*) estimated for the background hypothesis, i.e. if not co-moving, which can be rejected.

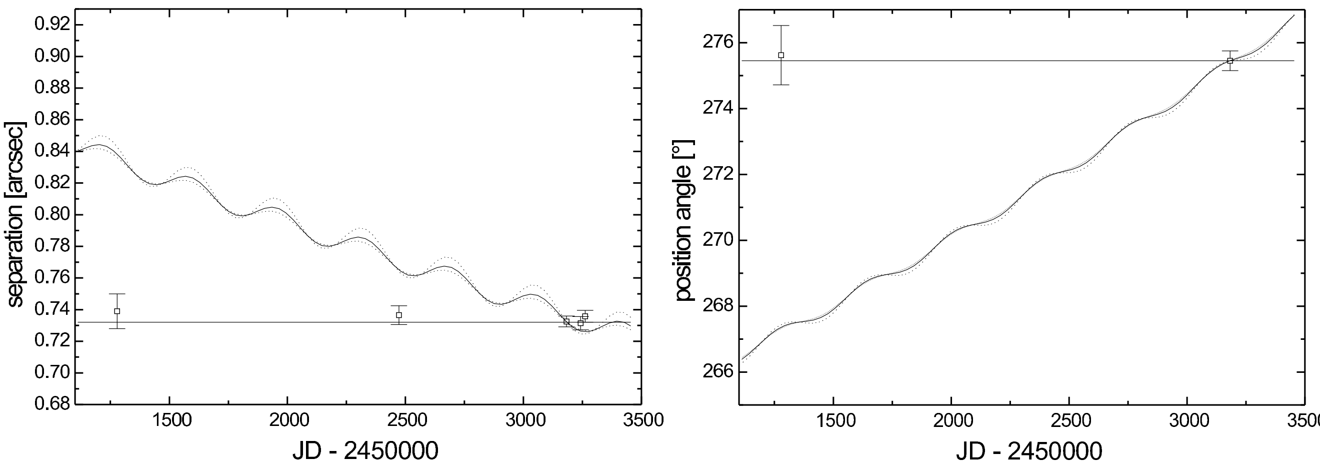

Fig. 5. The effect of the parallax uncertainty on the separation (left) and the position angle PA (right). We plot the data points from HST, Subaru and VLT (no position angle for Subaru, because those data were taken from the archive without calibration available to us) versus observing epoch. The full straight line indicates no change in separation. The curved full line is the expected separation for a parallax of 7.1 mas, the dotted lines for 5.3 mas and 11.1 mas (i.e. 140 ± 50 pc). The mean proper motion is used for GQ Lup A. The background hypothesis can be rejected by $\geq 10\sigma$ (see Table 3).

weighted mean proper motion, the significance for common proper motion is 6.9 σ by comparing the 1999 to 2004 separations, plus 3.9 σ by comparing the 2002 to 2004 separations, plus 7.8 σ by comparing the 1999 to 2004 PAs. These significances can be added up properly. In total, its well above 10 σ (and, hence, even higher than given in N05a using the Teixeira et al. (2000) proper motion only). Hence, GQ Lup A and the faint object west of it clearly form a common proper motion pair.

4. An alternative Interpretation

In principle, the two alternatives studied, namely that the companion (candidate) either has exactly the same proper motion as GQ Lup A or has neither proper nor parallactic motion at all, are unrealistic extremes. Even if the star and the faint object form a common proper motion pair as being gravitationally bound, one has to expect orbital motion, so that separation and/or PA change slowly but periodically (see below). And even if the two objects are not gravitationally bound, the fainter one does not necessarily have to stand still, it will have some proper and parallactic motion. If it is a background object, though, its proper and parallactic motion should be much smaller than for the primary star. But if it would be a foreground object, its motion could be larger than for GQ Lup A.

It is, however, very unlikely that two objects have exactly the same proper motion, but different distances: Our L1-2 companion could be either a $\sim$1 Myr planet of GQ Lup or a Gyrs old L1-2 dwarf at $\sim$26 pc ($\mathrm{M_K} = 11$ mag for L1-2, Tinney et al. 2003) with a space motion as high as to mimic the same proper motion as GQ Lup, or an intermediate-age object between 26 and 140 pc. With 100 field L-dwarfs brighter than K = 14 mag on the whole sky (spider.ipac.caltech.edu/staff/davy/ARCHIVE), the chance to find one within a circle with $0.7325''$ radius is $\leq 3 \cdot 10^{-10}$. The probability to find one such object also with the same proper motion is even smaller. The number is almost the same when considering the whole spectral type range of M9 to L4 given in N05a. Given 0.0057 ± 0.0025 L-dwarfs per pc^3 (Gizis et al. 2001), we expect only $\sim 2 \times 10^{-7}$ (or $\sim 5 \times 10^{-7}$, respectively) L-dwarfs in the frustum of a right circular cone between 26 and 140 pc (or even 190 pc, respectively), within a circle with $0.7325''$ radius. It is even less

Table 4. List of all estimated and observed separations and positions angles (PA), the significance to reject the background hypothesis is also given. The 2004 epoch is 25 June 2004, our deepest NACO image. No PA is available for Subaru 2002, because those data were taken by us from the public archive without calibration available.

PM	Epoch	Separation [mas]			PA [°]		
reference	difference	predicted (*)	observed	σ	predicted (*)	observed	σ
Carlsberg	1999-2004	844.0±21.1	739±11	4.4	267.1±1.4	275.62±0.86	5.2
	2002-2004	767.1±8.5	736.5±5.7	3.0			
Kharchenko	1999-2004	845.9± 21.1	739±11	4.5	267.0±1.4	275.62±0.86	5.3
	2002-2004	767.8± 8.5	736.5±5.7	3.1			
USNO	1999-2004	819.2±64.2	739±11	1.2	256.6±4.5	275.62±0.86	4.2
	2002-2004	750.1±24.1	736.5±5.7	0.6			
UCAC2	1999-2004	833.7±24.7	739±11	3.5	266.9±1.7	275.62±0.86	4.6
	2002-2004	763.2±9.7	736.5±5.7	2.4			
Camargo	1999-2004	811.5±16.0	739±11	3.7	267.3±1.1	275.62±0.86	6.0
	2002-2004	755.1±6.8	736.5±5.7	2.1			
Teixeira	1999-2004	878.4±21.1	739±11	5.9	269.9±1.4	275.62±0.86	3.5
	2002-2004	780.9±8.5	736.5±5.7	4.3			
weigthed	1999-2004	838.3±9.4	739±11	6.9	267.4± 0.6	275.62±0.86	7.8
mean	2002-2004	765.1±4.7	736.5±5.7	3.9			

Remark: (*) estimated for background hypothesis, i.e. if not co-moving, which can be rejected.

likely to find one within this circle or volume having even the same proper motion as GQ Lup A.

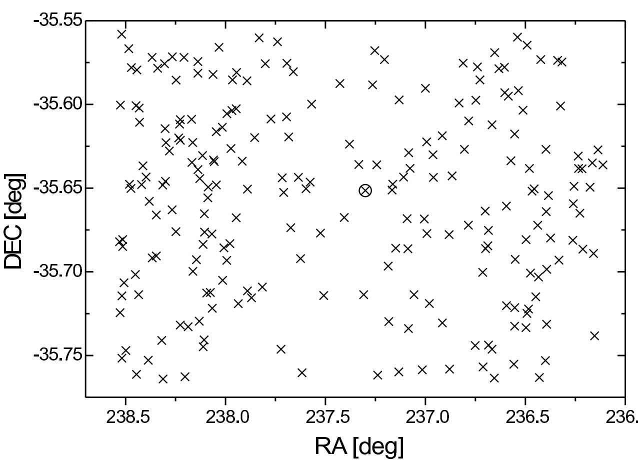

Fig. 6. Positions of all stars listed in Camargo et al. (2003) within 0.4 square degree around GQ Lup (indicated in the center).

a few pc). This is possible for all apparently common proper motion pairs, even in the field, but less unlikely in moving groups like T association and star forming clouds.

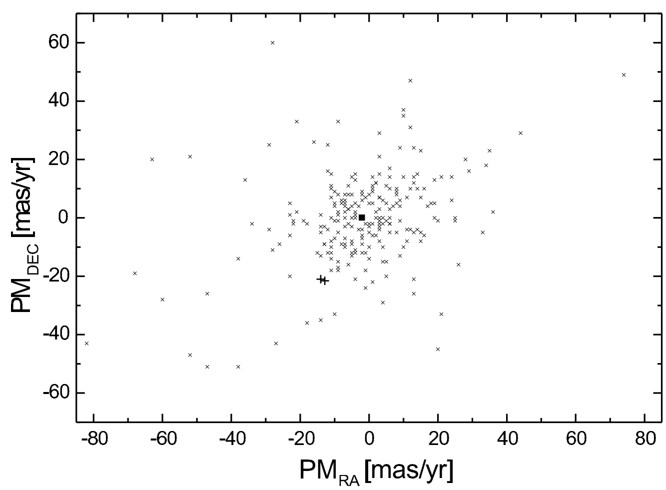

Fig. 7. Proper motions of stars listed in Camargo et al. (2003) within 0.4 square degree around GQ Lup. GQ Lup and its companion are plotted as black plus symbols and the average proper motion of all stars is shown as a black square.

4.1. Same proper motion, both in Lupus, but not bound ?

As discussed in Neuhäuser et al. (2002) for a late-M-type primary with a nearby fainter companion candidate in the Chamaeleon I cloud, which was later found to be a background giant (Neuhäuser et al. 2003), one has to take into account that most objects in a T association (like Chamaeleon and Lupus) do have a similar proper motion – except maybe some (or many ?) ejected run-away stars and brown dwarfs as well as possibly ejected planets (or planetary mass objects). Hence, even if GQ Lup A and the faint object show the same proper motion, they could be two gravitationally independent members of the Lupus association, i.e. two young objects in the Lupus I cloud at slightly different distances (even if only a few pc). This is possible for all apparently common proper motion pairs, even in the field, but less unlikely in moving groups like T association and star forming clouds.

Let us now estimate the likelihood for this scenario or the significance by which we can reject this possibility. There are 231 objects listed within 0.4 square degree around GQ Lup in Camargo et al. (2003) with proper motions known (we use the Camargo et al. catalog here, because it has the best precision in proper motions). The faintest detected objects in this catalogue exhibit a K - band magnitude of 13.1 mag, i.e. the brightness of GQ Lup b. Then, the probability to find one such object within 0.7325″ around one other star is only 0.000075 which is still regardless the (unlikely identical) proper motion.

According to our data in Table 2, the difference in proper motion between star and companion (candidate) is only

1.4 ± 2.2 mas/yr. None of the 231 stars within 0.4 square degree around GQ Lup has the same proper motion as GQ Lup; there is not even any star within 3 times the given relative motion around the GQ Lup proper motion (Camargo et al. 2003), except GQ Lup itself and its companion, see Fig. 7. The total area population by those 231 stars around GQ Lup in the proper motions phase space is $17316\,\mathrm{mas}^2/\mathrm{yr}^2$. However only a small fraction of stars exhibit high proper motions. The average proper motion of all star is $\mathrm{PM_{RA}}$=-2 mas/yr; $\mathrm{PM_{DEC}}$=0 mas/yr with a standard deviation of 17 mas/yr, assuming a normal distribution. The probability to find one object with a proper motion within 1.4 mas/yr of GQ Lup A is then only 0.049, considering the non-homogeneous, but normal distribution in Fig. 7.

Hence, the probability to find one Lupus object with both almost the same total proper motion and almost the same position of GQ Lup is only 0.000004, so that also this possibility can be rejected by $4\,\sigma$. And the probability to find one field L-dwarf (see above) with both almost the same proper motion and almost the same position of GQ Lup is only $\leq 3 \cdot 10^{-10}$, i.e. negligible.

4.2. The mean binary separation in Lupus

In Nakajima et al. (1998), the surface distribution of companions as function of angular separation is given for several different star forming regions including Lupus. From the power law fits in their equation 14 for Lupus, one would expect 0.116 objects with a separation of 0.7325″ to the next star. Hence, the fact that we find one such object is strongly deviant from the expectation (extrapolating their equation 14 for 1.0″ to 7.4″ slightly to 0.7325″).

Then, they specify the mean nearest neighbor distance (see their Fig. 5) being 10 times the so-called break point to be 7.4″ for Lupus, so that we get 1110 AU as mean nearest neighbor distance between any two objects in Lupus. In our case, we have a projected physical separation of ~ 100 AU, again very much different.

Hence, we can conclude that the possibility of two objects with almost the same position and the same proper motion, but slightly different distance within the Lupus I cloud, is very unlikely.

If there would be much more stars in Lupus I than known so far, e.g. strongly extincted within the cloud, i.e. much more than taken into account above, then it could be less unlikely that the faint object is not bound to GQ Lup A, but it would then become likely that it is bound to one of those many other, as yet unknown, stars in Lupus I; hence, it would still be a companion.

If the very unlikely possibility of same proper motion, but slightly different distances by just a few pc would be realized here, both objects would still be members of the Lupus I cloud, so that the distance and age estimate for the faint object is still correct (as in N05a), and hence, also the mass estimate. It would still be below the D burning mass limit, hence either a very low-mass (sub-)brown dwarf or an ejected planet.

4.3. Escape velocity in the GQ Lup and 2M1207 systems

Common proper motion is not a proof for being gravitationally bound. The lower the total mass and the larger the separation between the two co-moving companions, the lower the probability for being gravitationally bound. We can calculate this as ejection velocity of the companion and as binding potential of the system. To compare the recently presented system GQ Lup A and b with 2M1207 A and b in these regards, we need the masses of all components and the physical separation between them. According to the Wuchterl & Tscharnuter (2003) model GQ Lup A is a $\sim 0.7\,\mathrm{M_\odot}$ star; according to Hughes et al. (1994), when using the unpublished Swenson et al. models or the D'Antona & Mazzitelli (1994) models, the star may have $\sim$ 0.5 to $0.3\ \mathrm{M_\odot}$, respectively, with an age of only $\sim 10^6$ to $\sim 10^5$ yr, respectively, but it is dubious whether those two models are applicable at the young age of GQ Lup. The companion mass is negligible (we use $2\,\mathrm{M_{Jup}}$). The companion of the brown dwarf 2M1207 is separated by $0.772 \pm 0.004\,''$, being 54 ± 16 AU at 70 ± 20 pc as assumed in Chauvin et al. (2005), or just 41 ± 5 AU at 53 ± 6 pc as given in Mamajek (2005). The mass of the host brown dwarf A is assumed to be $\sim 25\,\mathrm{M_{Jup}}$, that of the companion b to be $\sim 5\,\mathrm{M_{Jup}}$ (Chauvin et al. 2004), but both mass estimates are very uncertain due to the low age and the fact that Chauvin et al. (2004) used only models which are not applicable at young ages. Mamajek (2005) give slightly lower mass estimates, but according to the same models which may not be applicable. For our calculations here, we use the values given in Chauvin et al. (2004).

Both companions are co-moving with their primaries, but the common proper motion of such systems is not a sufficient proof of companionship, because the escape velocity ($\sqrt{2\mathrm{GM/a}}$) for such wide companions is much smaller than the proper motion of the system barycenter.

Due to the unknown inclination and eccentricity of the orbits, it is difficult to predict exact escape velocities, so that we derive only rough estimates.

With the separation and the mass of the GQ Lup system, one would expect an escape velocity of 5.2 ± 2.1 mas/yr for the companion of GQ Lup. By comparing the HST astrometry from 1999 with the NACO data from 2005, we derive a relative motion between GQ Lup and its companion of only 1.4 ± 2.2 mas/yr, smaller than the expected escape velocity, but consistent with the expected orbital motion ($\mathrm{v_{esc}}/\sqrt{2} = 3.7 \pm 1.5$ mas/yr). These results tend to confirm that the common-proper motion pair GQ Lup is indeed bound. The measurement of the orbital motion of the companion with accurate NACO astrometry (4 mas) alone should be possible after a few more years of epoch difference.

Chauvin et al. (2005) present relative astrometry for both components and we derive a relative motion between both objects of 4.1 ± 8.2 mas/yr (using the data with the smallest astrometric uncertainties taken in April 2004 and Feb 2005)[2]. However, the small total mass and relatively large separation

[2] There seems to a typo in Chauvin et al. (2005): The predicted motion $\Delta\delta$ for the background hypothesis for Feb 2005 in given as -624 ± 10 mas in Table 2 in Chauvin et al. (2005), but only

of 2M1207 A and b yield an escape velocity of the companion of only 2.7 ± 0.9 mas/yr. The measured relative motion exceeds the escape velocity, but the uncertainty (8.2 mas/yr) is too large to conclude whether the companion of 2M1207 is indeed orbiting its host brown dwarf or is already disrupted (but still showing similar proper motion). With an expected orbital motion of 1.9 ± 0.6 mas/yr, one has to wait several more years to detected first indications of orbital motion with NACO, assuming again 4 mas astrometric accuracy.

4.4. Long-term stability of GQ Lup and 2M1207 systems

In the following, we will discuss the long-term stability of both systems. The binding potential $(-\mathrm{GM_{tot}}/2\mathrm{a})$ is used as indicator of the system stability against external disturbances, e.g. stellar encounters. We derive $(-3 \pm 1) \cdot 10^6$ J/kg for GQ Lup, but only $(-2.4 \pm 0.7) \cdot 10^5$ J/kg for 2M1207 at 70 ± 20 pc (or $(-3.1 \pm 0.4) \cdot 10^5$ J/kg at 53 ± 6 pc), i.e. the companion of GQ Lup is bound 10 to 13 times more tightly than the presented companion of 2M1207. Because both systems are located in star forming regions with increased stellar density, we expect that both systems will undergo or already have underwent several stellar encounters. Due to its higher stability, it is much more likely for the GQ Lup system to survive the remaining time in its star forming region than the 2M1207 system.

Even if both systems have survived their early time in the star forming region, they will undergo many encounters with other stars passing by in the galactic plane. These events will perturb the systems, slowly increasing their separations and eventually disrupting them. Following Weinberg et al. (1987), Close et al. (2003) derive that only systems closer than $\mathrm{a_{max}} = 1000(\mathrm{M_{tot}}/\mathrm{M_\odot})$ AU are close enough not to significantly evolve, i.e. not to disrupt in the galactic disc due to encounters with stars or clouds. In Fig. 8 we show total masses of binaries versus their separation. The given long-term stability limit in the galactic disk is illustrated as a solid line. Indeed most of the known binary systems are located within this stability region, i.e. left of the solid line. For a total mass of 0.7 $\mathrm{M_\odot}$ (GQ Lup), we find 700 AU as maximal separation of long-term stable systems, but only 29 AU for a total mass of 30 $\mathrm{M_{Jup}}$ (2M1207). With a separation of $\sim$ 54 AU (or 41 AU), the 2M1207 system exceeds this stability limit. It is therefore probable that it will be disrupted if it is still bound. In contrast, the companion of GQ Lup fulfills the stability criteria, hence this system should be long-term stable, like the giant planets in our solar system (see Fig. 8).

Close et al (2003) outline that very low-mass binaries are much tighter than their more massive counterparts with escape velocities all being higher than 3.8 km/s. They propose several scenarios explaining the observed differences, e.g. ejection theories where brown dwarfs are formed because they are ejected from their cluster by close encounters of other objects, being starved of accretion material. Only those systems survive which are the tightest bound, being observable today as common proper motion pairs. On the other hand brown dwarf binaries could also be the final remnants of a cluster decay, a process which is also only survived by tightly bound systems. The companion of 2M1207 is an exception of that rule because its escape velocity is only 0.9 ± 0.3 km/s, i.e. this system falls below the limit proposed by Close et al. (2003).

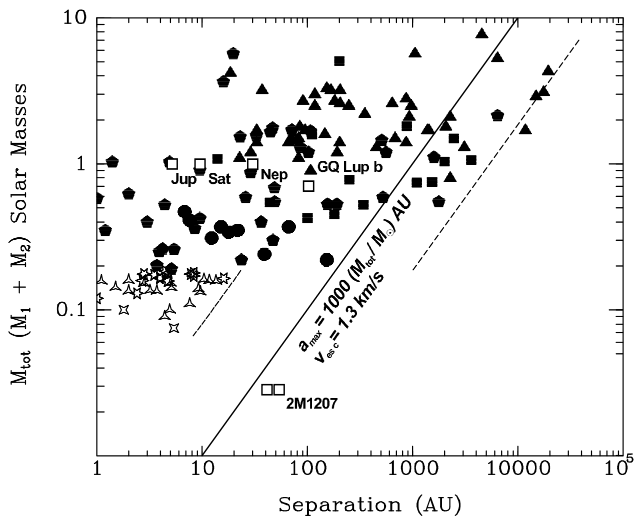

Fig. 8. The total mass of binary systems versus their separation from Close et al. (2003) with very low-mass binaries as open stars and normal stellar binaries as filled symbols. There are no low-mass systems with separations larger 16 AU. The escape velocity of the low-mass systems is about 3 km/s higher compared to more massive wide binaries. The solid line fit $\mathrm{a_{max}} = 1000(\mathrm{M_{tot}}/\mathrm{M_\odot})$ AU. Due to stochastic encounters, binary systems with separations larger than that limit should evolve to significantly wider orbits over time in the galactic disc, eventually being disrupted. The companions of 2M1207 and GQ Lup are shown with open squares together with the giant planets in our solar system. The GQ Lup system seems bound and long-term stable, the 2M1207 system not. The two symbols plotted for 2M1207 are for the two different distances published, for 70 pc (right) according to Chauvin et al. (2005) and for 53 pc (left) according to Mamajek (2005).

5. Summary and conclusions

We have shown that for any of the 6 proper motions published for GQ Lup A, the proposed companion (N05a) does indeed share its proper motion (by at least 6 σ). For the weighted mean proper motion, the common proper motion is very significant (6.9 σ + 3.9 σ + 7.8 σ).

Even if taking into account the large error in distance or parallax (140 ± 50 pc), the significance remains large. The effect of this error on the significance is only ± 0.3 dex.

Then, we also show that is it very unlikely that two objects with very similar proper motion are found within 0.7 arcsec on the sky. For the spectral type of the companion (L1-2), the probability of chance alignment is below $3 \cdot 10^{-10}$.

-424 ± 10 mas according to our own calculation; all other numbers in that table seem to be correct.

The mean nearest neighbor distance in Lupus is 1110 AU (Nakajima et al. 1998), while we observe a projected physical separation of ~ 100 AU.

We also show that the observed change in separation between GQ Lup A and b is smaller than the expected ejection velocity, so that the system is very likely bound. This is not yet shown for the 2M1207 system, where the observed change is separation may be larger than the expected ejection velocity. Also, the binding potential of the GQ Lup system is much larger than for the 2M1207 system, so that the former system is long-term stable, the latter is not. 2M1207 is less stable, even though of smaller separation, because of the lower masses of the components (as published in Chauvin et al. 2004). However, if the component masses would be larger, than the system could be bound and stable.

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